Dose-Response, 10:66–74, 2012
Formerly Nonlinearity in Biology, Toxicology, and Medicine
Copyright © 2012 University of Massachusetts
ISSN: 1559-3258
DOI: 10.2203/dose-response.11-010.Stark

International Dose-Response Society
www.Dose-Response.org

THE SANDPILE MODEL: OPTIMAL STRESS AND HORMESIS

Martha Stark □ Harvard Medical School

□ The sandpile model (developed by chaos theorists) is an elegant visual metaphor for the cumulative impact of environmental stressors on complex adaptive systems – an impact that is paradoxical by virtue of the fact that the grains of sand being steadily added to the gradually evolving sandpile are the occasion for both its disruption and its repair. As a result, complex adaptive systems are continuously refashioning themselves at ever-higher levels of complexity and integration – not just *in spite of* "stressful" input from the outside but *by way of* it. Stressful input is therefore inherently neither bad ("poison") nor good ("medication"). Rather, it will be how well the system (be it sandpile or living system) is able to process, integrate, and adapt to the stressful input that will make of it either a growth-disrupting (sandpile-destabilizing) event or a growth-promoting (sandpile-restabilizing) opportunity. Too much stress – "traumatic stress" – will be too overwhelming for the system to manage, triggering instead devastating breakdown. Too little stress will provide too little impetus for transformation and growth, serving instead simply to reinforce the system's status quo. But just the right amount of stress – "optimal stress" – will *provoke* recovery by *activating the system's innate capacity to heal itself.*

Keywords: sandpile model, complexity theory, hormesis, stress response

INTRODUCTION

As a psychoanalyst and holistic psychiatrist, I have long been interested in understanding how exactly it is that patients get better – in other words, what exactly it is that allows them to advance from illness to wellness. Over the course of the years, I have come increasingly to appreciate something that is probably quite obvious, namely, that it will be *input from the outside* and the patient's *capacity to process, integrate, and adapt to that input* that will enable the patient to get better.

In other words, for patients to progress from illness to wellness, there must be both environmental input (which constitutes the dose) and capacity of the system to manage that input (which constitutes the response).

This paper will address the paradoxical impact of stress on complex adaptive systems and will develop the idea that an optimal dose of stressful input, by triggering the body's innate ability to heal itself, will provoke "modest overcompensation" and a strengthening at the broken places.

As a psychoanalyst and holistic psychiatrist, the tools of my trade include psychological interventions, psychotropic medications, and an assortment of alternative therapies. The focus will first be on psychological interventions.

Address correspondence to Dr. Martha Stark, 3 Ripley Street, Newton, MA, 02459; Tel:617-244-7188; Email: marthastarkmd@hms.harvard.edu

CHALLENGE V. SUPPORT OF THE PATIENT'S DEFENSIVE STRUCTURE

Psychotherapists are ever busy formulating interventions that will either challenge or support – that is, challenge the patient by directing her attention to where she isn't (but where the therapist would like the patient to go) or support the patient by resonating with she is (and where the patient would seem to need to be).

Based on the therapist's moment-by-moment assessment of what the patient can tolerate, the therapist will therefore either challenge (by way of anxiety-provoking interpretive statements that call into question the defenses to which the patient has long clung in order to preserve her psychological equilibrium) or support (by way of anxiety-assuaging empathic statements that honor those self-protective defenses – a therapeutic stance often referred to as "going with the resistance").

Interventions that challenge will increase the patient's anxiety; interventions that support will decrease it (Stark 1999).

And if the therapist's interventions make the patient too anxious, the patient may "get defensive" and then be unable to take in – or benefit from – the therapist's input (because the patient will have become too overwhelmed to process and integrate it). But if the anxiety elicited by the therapist's interventions is more manageable, the patient may then be able to process and integrate the therapist's input and ultimately adapt to it by reconstituting at a higher level of self-awareness and complex understanding.

In truth, the patient can respond in any one of three ways to the therapist's input:

1. Too much challenge, too much anxiety, too much stress will be too overwhelming for the patient to process and integrate, triggering instead defensive collapse and temporary derailment of the therapeutic process.
2. Too little challenge, too little anxiety, too little stress will provide too little impetus for transformation and growth because there will be nothing that needs to be mastered; too little challenge will serve simply to reinforce the status quo.
3. But just the right amount of challenge, just the right amount of anxiety, just the right amount of stress – to which the father of stress, Hans Selye, referred as "eustress" – will offer just the right combination of challenge and support needed ultimately to prompt, perhaps after an initial (defensive) derailment, subsequent (adaptive) reconstitution at a higher level of order, complexity, and integration.

I therefore propose that, in order to optimize the potential for transformation and growth, the therapist must offer, in an ongoing fashion, an optimal balance of challenge and support – alternately challenging

(when possible) and supporting (when necessary) – such that an optimal level of anxiety will be provoked in the patient, anxiety that will then provide the impetus for the patient to evolve to a higher level of awareness, acceptance, and accountability – a higher level of complex orderedness and integrated coherence.

I am suggesting, more generally, that when the interface between stressor and system (that is, between the "dose" and the "response") is such that the system is able to process, integrate, and ultimately adapt to the cumulative impact of the stressful input, then the system will be able to progress to ever-higher levels of complexity – in other words, to ever-higher levels of organization and interrelatedness. But when the interface between stressor and system is such that the system is not able to process, integrate, and ultimately adapt – and, instead, simply defends – then the system will regress to a lower level of complexity.

In essence, adaptations involve higher-level processing and therefore a higher level of complexity, whereas defenses involve lower-level processing and therefore a lower level of complexity. A system that "can" will adapt, whereas a system that "can't" will defend. Psychoanalysts speak of the *capacity to adapt* and the *need to defend* (Stark 1999).

RECURSIVE CYCLES OF DEFENSIVE COLLAPSE AND ADAPTIVE RECOVERY IN CHAOTIC SYSTEMS

As happens with any open system, the patient's advancement from less-complex to more-complex is never simple, straightforward, or linear. Rather, evolution from illness to wellness is generally a much more protracted and unpredictable process involving multiple stops and starts, downs and ups, backward and forward movements, regressions and progressions, disruptions and repairs.

Briefly, in the language of complexity theory (Strogatz 1994; Kauffman 1995; Ho 1998; Buchanan 2000), an open system is chaotic (which speaks to the system's underlying orderedness despite its apparent randomness – an orderedness that will emerge as the system evolves), complex (which speaks to the interdependence of the system's constituent components), adaptive (which speaks to the system's capacity to benefit from experience), nonlinear (which speaks to the totally unpredictable but deeply patterned evolution of the system over time and in response to input from the outside), dynamical (which speaks to the emergence of novel structural configurations involving both repetition and innovation), and self-organizing (which speaks to the emergence of global patterns arising solely from local interactions between the system's constituent components).

Indeed, complexity theory has it that the internal structure of a self-organizing (or chaotic) system is intrinsically such that, in response to regulatory input from the environment, order will ultimately emerge

from chaos (Prigogine 1984; Strogatz 2003). This process of self-organization demonstrates nonlinearity, with erratic, often dramatic, and sometimes catastrophic transitions from one state of complexity to another whenever some critical threshold is reached (the timing for which is never knowable in advance).

So what patterns will emerge as the patient, here conceptualized as an open, self-organizing, chaotic system, advances from less-integrated to more-integrated, from less-coherent to more-coherent? I hypothesize that, over time and by way of input that either challenges or supports, healing cycles of disruption and repair will be induced, recursive cycles of disorganization and reorganization, defensive collapse and adaptive reconstitution at ever-higher levels of psychological complexity as the patient responds – either defensively (prompting collapse) or adaptively (prompting reconstitution) – to the ongoing *stressful input*.

In essence, psychotherapy affords the patient an opportunity, often long after the fact, to "manage" experience that had once been overwhelming – and therefore defended against – but that can now, with enough support from the outside, be processed, integrated, and adapted to. Psychotherapy is therefore a story about the belated processing of unmastered experience and, in the face of optimal challenge, adaptive reconstitution at ever-higher levels of awareness, acceptance, and accountability (Stark 1999).

THE SANDPILE MODEL AND THE PARADOXICAL IMPACT OF STRESS

Shifting now from patient to sandpile: Long intriguing to chaos theorists is the sandpile model (Bak *et al.* 1987; Bak 1996), which offers a dramatic depiction of the cumulative impact, over time, of environmental perturbations on open systems. The evolution of the sandpile is governed by some complex mathematical formulas and is well-known in many scientific circles but has rarely been applied to living systems and has never been used to demonstrate the paradoxical impact of stress on the living system.

I believe, however, that this simulation model provides an elegant visual metaphor for how the MindBodyMatrix (a term that I have coined to highlight the complex interdependence of mind and body) is continuously refashioning itself at ever-higher levels of complexity and integration – not just *in spite of* stressful input from the outside but *by way of* that input!

Amazingly enough, the grains of sand being steadily added to the gradually evolving sandpile are the occasion for both its disruption and its repair. Not only do the grains of sand being added precipitate partial collapse of the sandpile but also they become the means by which the sandpile is able to build itself back up – each time at a new level of homeostasis. The system will therefore have been able not only to *manage* the impact of the stressful input but also to *benefit from* that impact.

More specifically, with respect to the paradoxical impact of environmental stressors on the living matrix (Ball 2001; Oschman 2000; Braden 2007; Pischinger 2007), the difference between a poison and a medication is the dosage thereof (Paracelsus 2004). And, I would add, the system's capacity – a function of its underlying resilience – to process, integrate, and ultimately adapt to the impact of that stressor (Szent-Gyorgyi 1960).

In other words, stressful input is inherently neither bad (poison) nor good (medication).

Rather, the dosage of the stressor, the underlying adaptability of the system, and the intimate edge (Ehrenberg 1992) between stressor and system will determine whether the system, in response to the environmental input, defends and devolves to ever-greater disorganization or adapts and evolves, by way of a series of healing cycles, to ever-more complex levels of organization and dynamic balance.

In other words, if the interface between stressor and system is such that the stressor is able to provoke recovery within the system, then what would have been poison becomes medication, what would have constituted toxic input becomes therapeutic input, what would have been deemed traumatic stress becomes optimal stress, and what would have overwhelmed becomes transformative.

I am speaking here to the therapeutic use of stress to provoke recovery by activating the body's innate ability to heal itself (Cannon 1932; Sapolsky 1994; McEwen 1998; Bland 1999; McEwen 2002).

In essence, what doesn't kill you makes you stronger.

OPTIMAL STRESS

In the words of Ernest Hemingway, "The world breaks everyone; but, in the end, people are stronger at the broken places."

Stressful stuff happens all the time. But it will be how well the living system is able to process and integrate its impact – psychologically, physiologically, and energetically – that will make of it either a growth-disrupting (sandpile-destabilizing) event or a growth-promoting (sandpile-restabilizing) opportunity. In other words, it will be how well the MindBodyMatrix is able to manage the cumulative impact, over time, of environmental stressors that will either hasten a compromised system's deterioration or support a more resilient system's evolution toward increasing complexity.

So whether the primary target is mind or body and the clinical manifestation therefore psychiatric or medical, the critical issue will be the ability of the MindBodyMatrix to handle stress through adaptation. Again, too much stress will overwhelm and prompt defense; too little stress will offer too little opportunity for transformation and growth; but just the right amount of stress – optimal stress – will provide just the right amount of therapeutic leverage to induce, after initial disruption, adap-

tive reconstitution at ever-higher levels of complexity, integration, and adaptive capacity.

MINIMAL LOAD, OPTIMAL LOAD, AND OVERLOAD: FROM STABILITY THROUGH INCREASING COMPLEXITY TO CHAOS

Based upon study of the sandpile model, I postulate that – whatever the biological system, whatever the agent ("poison" or "medication"), whatever the endpoint ("health-promoting" or "disease-promoting"), and biochemical individuality notwithstanding (Williams 1956) – three distinct stages (Fig. 1) will inevitably emerge along the dose-response curve (here intended to represent the response, over time, of a single system to ongoing environmental input):

1. "minimal load" (the initial stage during which the system's homeostatic mechanisms will allow it to preserve both its status quo and its level of complexity);
2. "optimal load" (a compensatory stage during which the system's underlying resilience will enable it to evolve to ever-higher levels of complexity as it advances, over time, through iterative cycles of defensive collapse – a "minor avalanche" in chaos theory – and adaptive reconstitution); and

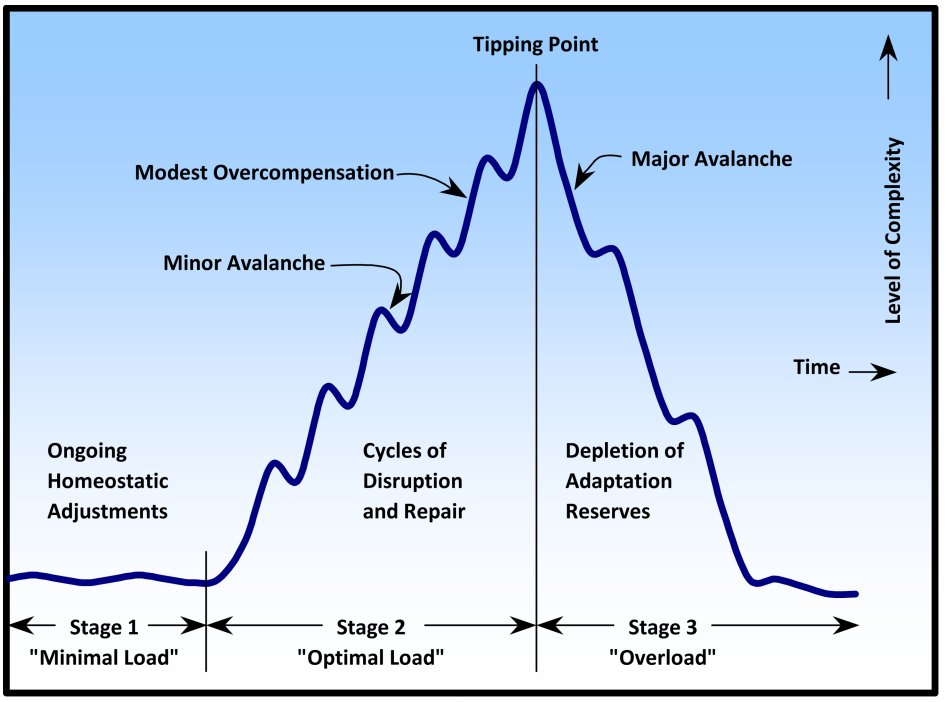

FIGURE 1. Nonlinear evolution of the sandpile over time.

3. "overload" (the terminal stage of decompensation during which the overburdened system – the load having exceeded the system's adaptive capacity – will sustain catastrophic collapse – a "major avalanche" in chaos theory – and devolve to a much lower level of complexity).

In other words, recursive cycles of disruption and repair will continue indefinitely, until some indeterminate point in time when a critical threshold will have been reached, a tipping point (Gladwell 2002), a saturation point, a point of toxic accumulation (Rea and Patel 2010) that will trigger a devastating, cataclysmic breakdown of the system – and the whole process will then begin anew, but this time from an entirely different baseline of complexity.

So the nonlinear evolution of a chaotic system proceeds from stability through increasing complexity to chaos. Initially, the system, in the face of minimal load, maintains itself, by way of ongoing homeostatic adjustments, at a baseline level of complexity. Then, in the face of optimal load, the system will evolve to ever-newer levels of homeostatic balance and ever-higher levels of complexity. Eventually, however, the system, in the face of overload and having exhausted its adaptation reserves, will collapse entirely, thereby devolving to a much lower level of complexity – and chaos.

With respect to the dose-response curve, I am therefore proposing that we consider the x-axis (the dose) to reflect the element of time and the y-axis (the response) to reflect the level of complexity in the system – a lower level of complexity going hand-in-hand with defensive reactions and a higher level of complexity going hand-in-hand with adaptive responses.

In sum: I believe that all living systems, in response to input from the outside, will evolve from minimal load through optimal load to overload; from minimal stress through optimal stress to traumatic stress (Selye 1974; Selye 1978); from unadapted through adapted to maladapted; from uncompensated through modestly overcompensated to decompensated; and from a state of homeostasis (which speaks to a single set point) through states of allostasis (which speak to ever-changing set points as the system adapts to ever-changing environmental conditions, in the process ever increasing its allostatic load) (Sterling 2004; Rea and Patel 2010) to a state of dyshomeostasis (which speaks to the system's inability to preserve any balance at all in the face of allostatic overload).

In other words, I believe that all living systems will evolve, given enough time, from stability through increasing complexity to chaos – by virtue of the fact that they are open, complex adaptive, nonlinear dynamical, self-organizing, and chaotic. Why will living systems evolve in this manner? For the very same unfathomable reason that a sandpile, in response to ongoing input from the outside, will advance through its cycles...

CONCLUSION

In closing: As we know, the hormetic effect speaks to the almost universal biphasic dose-response curve – a curve characterized by low-dose stimulation (whether secondary to *modest overcompensation to disruption in homeostasis* or to *direct stimulation*) and higher-dose inhibition (Calabrese and Baldwin 2003; Mattson and Calabrese 2010).

But if modest overcompensation (to an earlier disruption) is posited as one of the primary causes of low-dose stimulation (particularly with respect to "toxins"), then don't toxicology and pharmacology experiments need to be designed to factor in the element of time? In other words, if we want to be able, convincingly, to demonstrate the hormetic effect, then don't we need to conduct studies that track not just how different subjects will respond to different "doses of stress" but also how individual subjects will respond, over time, to the cumulative impact of stressful input?

In any event, my proposal is that we use the evolution of a sandpile to conceptualize the complex – and paradoxical – responsiveness of patients to the myriad of environmental stressors to which they are being continuously exposed. And my hope is that, eventually, the hormetic effect will come to be represented as not just a simple biphasic dose-response curve marked by one transition point but a complex series of nonmonotonic curves marked by multiple transition points (a complicated topological structure) – until the point of toxic overload, at which juncture the system will collapse entirely, only to resume its ongoing evolution from an entirely new baseline.

In celebration of hormesis, I have written a poem entitled "Optimal *Stress* and *Hormesis*"

Excess stress will cause mental and physical *distress*,
And, as time *passes*, *dyshomeostasis* and chronic *illness*.
But my *hypothesis* is that *less stress*, if well enough *processed*,
Will provide the *impetus* for healing and *wellness*,
And a strengthening at the broken *places* – 'cause of *hormesis*.

If a bone is fractured and then heals, the area of the break will be stronger than the surrounding bone and will not again easily break. Are we too not stronger at our broken places? And is there not a certain beauty in brokenness, a beauty never achieved by things unbroken? Do we not acquire a quiet strength from surviving adversity and hardship and mastering the experience of disappointment and heartbreak? And then, when we finally rise above it, do we not rise up in quiet triumph, even if only we notice?

REFERENCES

Bak P. 1996. How Nature Works: The Science of Self-organized Criticality. Springer-Verlag, New York, NY

Bak P, Tang C, and Wiesenfeld K. 1987. Self-organized criticality: An explanation of 1/f noise. Physical Review Letters 59(4).

Ball P. 2001. Life's Matrix. University of California Press, Berkeley, CA

Bland J. 1999. Genetic Nutritioneering. McGraw-Hill Book Co., New York, NY

Braden G. 2007. The Divine Matrix: Bridging Time, Space, Miracles, and Belief. Hay House, Carlsbad, CA

Buchanan M. 2000. Ubiquity: Why Catastrophes Happen. Three Rivers Press, New York, NY

Calabrese EJ and Baldwin LA. 2003. The hormetic dose-response model is more common than the threshold model in toxicology. Toxicol Sci 71(2):246-50.

Cannon WB. 1932. The Wisdom of the Body. W. W. Norton & Company, New York, NY

Ehrenberg D. 1992. The Intimate Edge: Extending the Reach of Psychoanalytic Interaction. W. W. Norton & Company, New York, NY

Gladwell M. 2002. The Tipping Point: How Little Things Can Make a Big Difference. Little, Brown and Company, New York, NY

Ho MW. 1998. The Rainbow and the Worm: The Physics of Organisms. World Scientific, River Edge, NJ

Kauffman S. 1995. At Home in the Universe: The Search for the Laws of Self-Organization and Complexity. Oxford University, New York, NY

McEwen BS. 1998. Stress, adaptation, and disease. Allostasis and allostatic load. Ann NY Acad Sci 840:33-44

McEwen BS. 2002. The End of Stress As We Know It. Joseph Henry Press, Washington, DC

Mattson MP and Calabrese EJ (eds). 2010. Hormesis: A revolution in biology, toxicology and medicine. Springer-Verlag, New York, NY

Oschman JL. 2000. Energy Medicine: The Scientific Basis. Churchill Livingstone, New York, NY

Paracelsus T. 2004. The Archidoxes of Magic. Turner R (trans). Ibis Publishing, Temecula, CA

Pischinger A. 2007. The Extracellular Matrix and Ground Regulation: Basis for a Holistic Theory in Medicine. Heine H (ed). North Atlantic Books, Berkeley, CA

Prigogine I. 1984. Order Out of Chaos: Man's New Dialogue with Nature. Bantam Books, New York, NY

Rea WJ and Patel K. 2010. Reversibility of Chronic Degenerative Disease and Hypersensitivity: Regulating Mechanisms of Chemical Sensitivity. Volume 1. Taylor & Francis Group, CRC Press, Boca Raton, FL

Sapolsky RM. 1994. Why Zebras Don't Get Ulcers. W. H. Freeman and Company, New York, NY

Selye H. 1974. Stress without Distress. Harper & Row, Publishers, Inc., New York, NY

Selye H. 1978. The Stress of Life. McGraw-Hill Book Co., New York, NY

Stark M. 1999. Modes of Therapeutic Action: Enhancement of Knowledge, Provision of Experience, and Engagement in Relationship. Jason Aronson, Northvale, NJ

Sterling P. 2004. Principles of allostasis: Optimal design, predictive regulation, pathophysiology, and rational therapeutics. In: Schulkin J (ed), Allostasis, Homeostasis, and the Costs of Physiological Adaptation, pp. 17-64. Cambridge University Press, New York, NY

Strogatz S. 1994. Nonlinear Dynamics and Chaos: With Applications to Physics, Biology, Chemistry, and Engineering. Perseus Books, Cambridge, MA

Strogatz S. 2003. Sync: How Order Emerges from Chaos in the Universe, Nature, and Daily Life. Hyperion, New York, NY

Szent-Gyorgyi A. 1960. Introduction to a Submolecular Biology. Academic Press, New York, NY

Williams RJ. 1956. Biochemical Individuality: The Basis for the Genetotrophic Concept. Keats Publishing, New Canaan, CT